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UTILITY PATENT APPLICATION TRANSMITTAL LETTER AND FEE TRANSMITTAL FORM (37 CFR 1.53(b))

BOX PATENT APPLICATION
Commissioner for Patents
Washington, DC 20231

Sir:

Transmitted herewith for filing under 37 CFR 1.53(b) is:
☒ a patent application
☐ a Continuation ☐ a Divisional ☐ a Continuation-in-Part (CIP)
of prior application no.: ; filed
☐ A Small Entity Statement(s) was filed in the prior application; Status still proper and desired.

Inventor(s) or Application Identifier:

Karl James Molnar; Abdulrauf Hafeez; Hüseyin Arslan

Entitled: AUTOMATIC FREQUENCY CONTROL SYSTEMS AND METHODS FOR JOINT DEMODULATION

Enclosed are:
1. ☒ Application Transmittal Letter and Fee Transmittal Form *(A duplicate is enclosed for fee processing)*
2. ☒ 24 pages of Specification (including 44 claims)
3. ☒ 8 sheets of Formal Drawings (35 USC 113)
4. ☒ Oath or Declaration
   a. ☒ newly executed *(original or copy)*
   b. ☐ copy from prior application (37 CFR 1.63(d) *(for continuation/divisional)* **[Note Box 5 Below]**
   c. ☐ DELETION OF INVENTOR(S) *(Signed statement deleting inventor(s) named in the prior application)*
5. ☐ Incorporation By Reference *(useable if box 4b is checked)*
   The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.
6. ☐ Microfiche Computer Program *(Appendix)*
7. ☒ Assignment papers *(cover sheet(s) and document(s))*
8. ☐ Small Entity Statement(s)
9. ☒ Information Disclosure Statement, PTO-1449, and 9 of 10 references cited
10. ☐ Preliminary Amendment ***(Please enter all claim amendments prior to calculating the filing fee.)***
11. ☐ English Translation Document
12. ☐ Certified Copy of Application No. ; Filed

13. ☐ Sequence Listing/ Sequence Listing Diskette
    a. ☐ computer readable copy
    b. ☐ paper copy
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14. ☐ An Associate Power of Attorney
15. ☒ Return Receipt Postcard (MPEP 503) *(Should be specifically itemized)*
16. ☐ Other:

The fee has been calculated as shown below:

	Column 1 No. Filed	Column 2 No. Extra	Small Entity Rate Fee	Large Entity Rate Fee
BASIC FEE			$355.00	$710.00
TOTAL CLAIMS	44 - 20 =	24	x 9 = $	x 18 = $432.00
INDEP CLAIMS	5 - 3 =	2	x 40 = $	x 80 = $160.00
☐ MULTIPLE Dependent Claims Presented			+ 135 = $	+ 270 = $
If the difference in Col. 1 is less than zero, Enter "0" in Col. 2			Total $	Total $1302.00

☐ A check in the amount of $ to cover the filing fee is enclosed.

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☒ The Commissioner is hereby authorized to charge payment of the following fees associated with this communication or credit any overpayment to Deposit Account No. 50-0220.
- ☒ Any additional filing fees required under 37 CFR 1.16.
- ☒ Any patent application processing fees under 37 CFR 1.17.

Respectfully submitted,

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CERTIFICATE OF EXPRESS MAILING

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Susan E. Freedman
Date of Signature: October 30, 2000

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

Attorney Docket No. 8194-392

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled AUTOMATIC FREQUENCY CONTROL SYSTEMS AND METHODS FOR JOINT DEMODULATION,

the specification of which

☒ is attached hereto

OR

☐ was filed on _____ as United States Application No. or PCT International Application Number and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37 Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, § 119(a)-(d) or § 365(b) of any foreign application(s) for patent or inventor's certificate, or § 365(a) of any PCT International application which designated at least one country other than the United States of America, listed below and have also identified below any foreign application for patent or inventor's certificate, or of any PCT International application having a filing date before that of the application on which priority is claimed.

None			☐ Yes ☐ No
Number	Country	MM/DD/YYYY Filed	Priority Claimed
			☐ Yes ☐ No
Number	Country	MM/DD/YYYY Filed	Priority Claimed

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below.

None	
Application Number(s)	Filing Date (MM/DD/YYYY)
Application Number(s)	Filing Date (MM/DD/YYYY)

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) or § 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application(s) in the manner provided by the first paragraph of Title 35, United States Code, § 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, § 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application (37 C.F.R. § 1.63(d)).

None		
Appln. Serial No.	Filing Date	Status Patented/Pending/Abandoned
Appln. Serial No.	Filing Date	Status Patented/Pending/Abandoned

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following registered attorney(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

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AUTOMATIC FREQUENCY CONTROL SYSTEMS AND METHODS FOR JOINT DEMODULATION

BACKGROUND OF THE INVENTION

This invention relates to digital communications, and more particularly to systems and methods for jointly demodulating a received signal.

Joint demodulation is widely used to detect two or more signals that are received over a common channel. For example, joint demodulation may be used to detect a desired signal from a received signal that includes an interfering signal as well. In joint demodulation, the desired signal and the interfering signal are both demodulated based on information concerning the desired signal and the interfering signal, so as to obtain a better estimate of the desired signal.

Two-user joint demodulation for IS-136 TDMA wireless communication terminals has been proposed for cancellation of a dominant interfering signal, also referred to as an "interferer", under the assumptions of a flat, slow fading downlink environment. By subtracting off the interfering signal, the desired signal's bit error-rate can be improved. This occurs since both the channel and symbol data corresponding to the interferer generally are not perfectly correlated to the desired signal, allowing separation of the two signals. Joint demodulation thus may rely upon the ability to estimate the channel and perform symbol detection for each user across the data slot.

For the joint demodulation approach used for the IS-136 system, estimation of the initial channel response generally is performed in the same manner as in conventional single-user demodulation since the synchronization (sync) sequence for the desired signal is known. However, since the interferer sync word generally is unknown, a semi-blind technique may be used to find an estimate of the sample-position offset and the initial channel response of the interferer. Joint detection of the two users' symbol data then may be performed, for example using per-survivor processing using LMS tracking of the channel responses for each user.

A concern in the implementation of joint demodulation is the impact that frequency offset of the users' signals will have on the ability to cancel interference. In

single-user demodulation, the carrier frequency of the received signal may be offset from the assumed carrier frequency, for example due to the limited tolerance of the oscillators in the base station and/or wireless terminal. Correcting for this frequency offset is typically a two-step Automatic Frequency Control (AFC) process, that includes initial frequency acquisition and frequency tracking. Frequency tracking can estimate and track the residual frequency offset that remains after initial frequency acquisition, and itself may be a two-step process including long term AFC and local (short term) AFC estimation.

SUMMARY OF THE INVENTION

Embodiments of the present invention can provide systems and methods for jointly demodulating jointly received first and second signals, wherein a joint demodulator is configured to generate an estimated first frequency or first frequency error for the first signal and an estimated second frequency or second frequency error for the second signal. A first long-term automatic frequency control is responsive to the estimated first frequency or first frequency error, wherein the joint demodulator is responsive to the first long-term automatic frequency control. A second long-term automatic frequency control is responsive to the estimated second frequency or second frequency error, wherein the joint demodulator is responsive to the second long-term automatic frequency control. First and second local automatic frequency controls also may be included in the joint demodulator, wherein the first long-term automatic frequency control is responsive to the first local automatic frequency control and the second long-term automatic frequency control is responsive to the second local automatic frequency control.

In some embodiments, the first long-term automatic frequency control and the second long-term automatic frequency control produce respective first and second frequency offset signals that are applied to the joint demodulator. In other embodiments, a difference between the first and second frequency offsets is applied to the joint demodulator and the first frequency offset is applied to a downconverter that downconverts the jointly received first and second signals and provides the downconverted signals to the joint demodulator. Thus, in these embodiments, the frequency offset of the desired signal is used to correct the incoming signal at the local oscillator of the downconverter.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a conventional long term AFC loop.

Figure 2 graphically illustrates relative frequency offset of an interferer according to embodiments of the present invention.

Figures 3 and 4 are block diagrams of alternate embodiments of joint demodulation systems and methods according to the present invention.

Figure 5 is a block diagram of embodiments of systems and methods for long term AFC for two user joint demodulation according to the present invention.

Figure 6 is a block diagram of embodiments of PSP MLSE according to embodiments of the present invention.

Figure 7 is a block diagram of multiple survivor MLSE according to embodiments of the present invention.

Figure 8 is a block diagram of metric calculation for two user joint demodulation according to embodiments of the present invention.

Figure 9 is a block diagram of channel estimation for two user joint demodulation according to the present invention.

Figure 10 is a block diagram of local and long term AFC for two user joint demodulation according to embodiments of the present invention.

Figure 11 is a block diagram of phase error computation for two user joint demodulation according to embodiments of the present invention.

Figure 12 is a block diagram of second order phase lock loops that can be used for joint demodulation according to embodiments of the present invention.

Figures 13 and 14 are block diagrams of adaptive demodulation with new frequencies output and with new frequency errors output, respectively, according to embodiments of the present invention.

Figure 15 graphically illustrates simulation results of joint AFC according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and

complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout. It will be understood that when an element is referred to as being "coupled" or "connected" to another element, it can be directly coupled or connected to the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly coupled" or "directly connected" to another element, there are no intervening elements present.

A block diagram of a long term AFC loop for a single-user detector is shown in Figure 1. As shown in Figure 1, a received signal is received at an antenna **102** and is downconverted by converter **104**. The signal then may be filtered by a filter **106**, passed through an analog-to-digital converter, sampled and sent to a synchronizer **108**. The signal can be sampled once per symbol or multiple times per symbol, as in the IS-136 standard.

The synchronizer **108** synchronizes the signal and can further sample the output signal at a rate to be processed by a detector using one or more samples per symbol. In this embodiment, the detector **110** is a Maximum Likelihood Sequence Estimator (MLSE) which provides a demodulated output signal. In addition, a long term AFC loop **112** is responsive to a frequency error signal $f_{d,err}$, applied to a smoothing filter **114** to generate a frequency precorrection signal $f_{d,n}$ that is applied to the next data slot at the converter **104**.

For joint demodulation at a wireless terminal, the frequency offset for multiple users may arise from the different base stations that transmit the users' signals. For joint demodulation of a desired signal and an interfering signal, the frequency offset may arise due to frequency offsets between the desired signal and the interfering signal. Assume that coarse frequency acquisition has been performed with respect to the desired signal's base station. Further, assume that a residual frequency error of ±200 Hz exists between the base station carrier and the true carrier frequency, and that the mobile terminal can lock to within ±200 Hz with respect to the desired base station carrier frequency after coarse acquisition. Under these assumptions, the maximum frequency errors from the mobile to the desired and interfering base stations are ±200 Hz and ±600 Hz, respectively.

One approach for compensation of frequency offsets together with joint demodulation is described in Murata et al., *Joint Frequency Offset and Delay Profile Estimation Technique for Nonlinear Co-Channel Interference Canceller*, Proc. PIMRC, November 1998, pp. 486-490. Murata et al. describes a slot-aligned TDMA

system where all users' sync sequences are known. The sync sequences are used in training mode to estimate the frequency offsets for each user jointly, and these frequency estimates are then fixed for the subsequent demodulation across the unknown data burst.

The joint AFC approach used in the Murata et al. publication appears to be similar to the single-user AFC approach described above. However, it may not perform adequately for semi-blind joint demodulation. In particular, the desired signal frequency is not used to precorrect the local oscillator frequency prior to synchronization or demodulation. This correction may be desirable if the corrected receive frequency is used as a reference for the transmit frequency, as is true for many IS-136 wireless terminals.

Moreover, in the Murata et al. publication, the frequency offsets are estimated directly over the sync sequence and then applied as a phase correction to the hypothesized signal in the metric when demodulating the data burst. Since frequency is the derivative of phase, it may be a noisy estimate, and a phase tracker may need to be used. Finally, in a semi-blind joint demodulation approach, the sync sequence for the interferer is unknown. Thus, both the channel and frequency estimates of the interferer are not very reliable after training. Instead of fixing the frequency estimate for data demodulation, it would be desirable to track it instead. Unfortunately, AFC loops, in general, are designed for tracking small frequency errors. Thus, it may be preferred to track the residual frequency error, i.e., the difference between the estimated frequency offset and the true frequency offset.

Embodiments according to the present invention now will be described. These embodiments can assume that the precorrection of the frequency for the desired signal is performed prior to filtering and synchronization. This impacts the relative frequency offset of the second signal, such as an interfering signal, also referred to as an "interferer", to a converter such as a local oscillator (LO) at the receiver.

For example, as shown in Figure 2, a wireless terminal, also referred to as a mobile station (MS), has a 200 Hz offset from transmitters such as base stations BS1 (desired) and BS2 (interferer). If the mobile station corrects its frequency to align itself with BS1, then it may be 400 Hz offset from BS2. When the frequency correction is applied, then f_{BS2}-f_{BS1} is the frequency offset from the mobile station to the interferer, when f_{MS} becomes f_{BS1}. In estimating the frequency offsets directly, this may present a problem since the offsets change relative to the mobile carrier f_{MS}.

Instead, according to embodiments of the invention, an estimate of the frequency offsets relative to a reference is obtained, so that the fixed frequency offset need not change after applying the frequency precorrection. Additionally, in the MLSE, it may be desired to track the residual frequency error as this will, hopefully, be small after some settling time. To do this, embodiments of the invention may account for the fixed-frequency terms in the MLSE metric and channel estimator.

Referring now to Figure 3, first embodiments of systems and methods **300** for demodulating jointly received first and second signals according to the present invention, now will be described. As shown in Figure 3, a converter **310**, such as a baseband converter or baseband demodulator, is configured to downconvert jointly received first and second signals **S1** and **S2**. A joint demodulator **320** is responsive to the downconverted, jointly received first and second signals, and is configured to separately generate an estimated first frequency **f1** or an estimated first frequency error **f1,err** for the downconverted first signal, and an estimated second frequency **f2** or an estimated second frequency error **f2,err** for the downconverted second signal. As shown in Figure 3, the joint demodulator **320** may include a first local AFC **322a** and a second local AFC **322b** that may be used to generate the first frequency/first frequency error and the second frequency/second frequency error, respectively.

Still referring to Figure 3, a first long-term automatic frequency control **330a** is responsive to the first frequency/first frequency error, to generate a first frequency offset $\overline{\mathbf{f1}}$ that is applied to the joint demodulator **320**. A second long-term automatic frequency control **330b** is responsive to the second frequency/second frequency error, to generate a second frequency offset $\overline{\mathbf{f2}}$ that is applied to the joint demodulator. Thus, the joint demodulator is responsive to both the estimated second frequency/second frequency error and the estimated first frequency/first frequency error, to jointly demodulate the downconverted jointly received first and second signals.

Referring now to Figure 4, second embodiments of systems and methods **400** for demodulating jointly received first and second signals are shown. As shown in Figure 4, a converter **310**, a joint demodulator **320** including first local AFC **322a** and second local AFC **322b** and first and second long-term AFC **330a** and **330b** respectively can operate as was described above in connection with Figure 3. In Figure 4, a subtractor **440** also is provided, wherein the difference between the first

frequency offset $\overline{\mathbf{f1}}$ and the second frequency offset $\overline{\mathbf{f2}}$ is generated and applied to the joint demodulator **320**. In these embodiments, the joint demodulator assumes that there is no first frequency error, as illustrated in Figure 4.

Additional discussion of the embodiments of Figures 3 and 4 now will be provided. In embodiments of the invention, the first signal **S1** may be a desired signal and the second signal **S2** may be an interfering signal. Moreover, the jointly received first and second signals may be received over a series of repeating slots and are sampled more than once during each slot. The local AFC **322a** and **322b** can operate at a first rate and the long-term AFC **330a** and **330b** can operate at a second rate that is lower than the first rate. In some embodiments, the first rate is once per sample, and the second rate is once per slot. The outputs from the local AFC **322a** and **322b** can be either an estimate of the frequency offset or an estimate of the error in the frequency offset. The long-term AFC **330a**, **330b** can be configured to handle either kind of estimate from the input. A fixed frequency term can be input to the local AFC **322a**, **322b**, so that the local AFC only estimates the error frequency.

In Figure 4, the desired signal's frequency estimate $\overline{\mathbf{f1}}$ can be sent to the local oscillator in the converter **310**, to correct the signal prior to demodulation. Alternatively, in embodiments of Figure 3, the desired signal's frequency offset $\overline{\mathbf{f1}}$ can be sent directly to the joint demodulator.

Figure 5 is a block diagram of other embodiments of joint demodulation systems and methods according to the invention. Referring to Figure 5, the joint demodulator **320** outputs estimates of the residual frequency errors **f1,err** and **f2,err** for each user after demodulating a slot of data. These residual error estimates each are input to long term AFC loops **330a**, **330b**, each of which includes a smoothing filter **560a**, **560b**, to calculate the total frequency offset for each user. The desired signal frequency offset $\overline{f1}$ is applied to the local oscillator **530** of the converter **310** while the difference $\overline{f2} - \overline{f1}$ from summer **440** is applied to the joint demodulator **320** as the initial frequency offset for the interferer. Also shown explicitly is that zero frequency offset **550** is input to the joint demodulator **320** as the initial frequency offset for the desired signal. A conventional filter **532** and synchronizer **534** also are used in the converter **310**. The smoothers **560a**, **560b** operate as the long term AFC **330a**, **330b**, when connected as shown.

A description of metric computation and channel estimation for joint demodulation in the joint demodulator **320** now will be described. For the two-user case with symbol-spaced receive samples, the receive signal is modeled at the *l*th sample using

$$y_l = \hat{y}_{1,l} e^{j\phi_{1,err}} + \hat{y}_{2,l} e^{j\phi_{2,err}}, \quad (1)$$

where the terms $\phi_{1,err}$ and $\phi_{2,err}$ represent the phase error for the desired and interfering users, respectively, given that the phase has been estimated and corrected up through time *l*. The term $\hat{y}_{i,l}$ is the hypothesized receive signal for user i precorrected up to sample *l*, and is given by

$$\begin{aligned} \hat{y}_{i,l} &= \sum_{k=0}^{K_i-1} c_{i,k,l} s_{i,l-k} e^{j2\pi f_i l T_s} e^{j\phi_{i,l}} \\ &= e^{j2\pi f_i l T_s} e^{j\phi_{i,l}} \boldsymbol{c}_{i,l}^{T} \boldsymbol{s}_{i,l} \end{aligned}, \quad (2)$$

where K_i is the number of dispersive taps for user i. The hypothesized signal contains the fixed frequency component f_i for each user, which does not vary across the slot. Alternatively, the fixed frequency component f_i can be set to zero and incorporated as the initial value of the frequency component of the second order phase-locked loop. The adaptive phase error term $\phi_{i,l}$ is the phase correction applied after demodulating the (*l*-1)st receive sample. Assume that this phase error is modeled by a second-order digital phase-locked loop, as in the single-user case, so that residual frequency error can be estimated for each user. The objective is then to determine how to calculate the phase error terms $\phi_{i,err}$ for users i=1 and i=2, which are then used to form the updated phase corrections $\phi_{i,l+1}$.

Both Per Survivor Processing (PSP) and multiple-survivor MLSE may be used for joint demodulation. In each case, branch metrics are generated for hypothesized paths in the MLSE trellis. For PSP-MLSE, as shown in Figure 6, the path corresponding to the best total accumulated metric **610a-610m** at the input of each new state is declared a surviving path at block **620**. For multiple-survivor MLSE with QPSK signaling, as shown in Figure 7, the accumulated metrics **710a-710m** are ranked at block **720** and the M paths with the best metrics survive to be further propagated. In each case, the channel and AFC estimates are updated for the surviving states or paths at block **630** and **730**, respectively.

Embodiments of metric generation, for example blocks **610** and **710** of Figures 6 and 7, respectively, now will be described in Figure 8. For each new branch from an existing state (path), the error value e_l is computed. First, the symbol data and channel data are used at block **810** to calculate the signals $y_{i,l} = c_{i,l}^T s_{i,l}$ for each user i $\in \{1,2\}$, corresponding to the receive signal in the absence of frequency error. Next, the fixed frequency error term f_i is combined at blocks **830a** and **830b** with the most recent phase correction term $\phi_{i,l}$ from block **820**, and this is used to rotate $y_{i,l}$ in the complex plane, forming $\hat{y}_{i,l}$ using blocks **840a** and **840b**. The error term is then formed using blocks **850** and **860** which is used to compute the branch metric. The term $p_{i,l}$ represents the complex rotation performed on $y_{i,l}$ and is given as

$$p_{i,l} = e^{j2\pi f_i l T_s} e^{j\phi_{i,l}}. \quad (3)$$

Certain variables may be temporarily saved at this point for each best path so that they may be used in the subsequent channel or AFC update. The terms e_l, $p_{i,l}$, $s_{i,l}$ may be saved for performing the channel update, while $\hat{y}_{i,l}$ may be saved for performing the AFC update. Note, that in U.S. Patent Application Serial No. 09/143,821 to Hafeez et al. entitled *Methods And Systems for Reducing Co-Channel Interference Using Multiple Timings For A Received Signal*, $s_{i,l}$ may correspond to the symbol information filtered by a known pulse-shape and may not be the symbol data itself (which is why it should be saved). Also preferably saved as part of the traditional PSP-MLSE or MS-MLSE is the symbol history, channel and phase error states that get propagated for each surviving path.

The channel update can then be performed for two-user joint demodulation as shown in Figure 9, using the temporarily saved path variables described above. The phase correction term is applied to the error signal at blocks **910a** and **910b**, which is common to each channel update block **920**, for a single user. Additionally, for the metric calculation, the phase correction is applied to $y_{i,l}$, rather than the symbol data. Performing the phase correction in this manner may use fewer operations than the approach used in the Murata et al. publication, where symbol values may need to be rotated for each possible branch metric in the trellis.

Local AFC for joint demodulation according to embodiments of the invention now will be described. The update may be determined for calculating the phase error terms to be used in the AFC loop. Equation (4) describes the received sample after

frequency correction, where the residual phase errors $\phi_{1,err}$ and $\phi_{2,err}$ are to be found. In order to find these phase errors, the following metric may be used:

$$\gamma = -\frac{1}{N}\left|y_l - \hat{y}_l^T w_l^*\right|^2, \tag{4}$$

assuming zero-mean AWGN noise and no further interference. The terms $\hat{y}_l^T = \left[\hat{y}_{1,l}\ \hat{y}_{2,l}\right]$ and $w_l^* = \left[e^{j\phi_{1,err}}\ e^{j\phi_{2,err}}\right]^T$. Then, expanding γ gives

$$\begin{aligned}\gamma &= -\left|y_l\right|^2 + 2\,\mathrm{Re}\left\{y_l^* \hat{y}_l^T w_l\right\} + \left|\hat{y}_l^T\right|^2 \\ &= -2\,\mathrm{Re}\left\{y_l^* \hat{y}_{1,l} e^{j\phi_{1,err}} + y_l^* \hat{y}_{2,l} e^{j\phi_{2,err}} - \hat{y}_{1,l} y_{2,l}^* e^{j(\phi_{1,err}-\phi_{2,err})}\right\}\end{aligned} \tag{5}$$

An equivalent metric for γ is

If an estimate is made of $\phi_{1,err}$, with $\phi_{2,err}$ fixed, γ can be maximized using only those terms containing $\phi_{1,err}$. Thus,

$$\begin{aligned}\hat{\phi}_{1,err} &= \arg\max_{\phi_{1,err}} \gamma \\ &= \arg\max_{\phi_{1,err}} \mathrm{Re}\left\{e^{j\phi_{1,err}} \hat{y}_{1,l}\left[y_l^* - y_{2,l}^* e^{-j\phi_{2,err}}\right]\right\}\end{aligned} \tag{6}$$

To maximize this quantity, $\phi_{1,err}$ may be chosen such that

$$\hat{\phi}_{1,err} = \arg\left\{\hat{y}_{1,l}^*\left[y_l - \hat{y}_{2,l} e^{j\phi_{2,err}}\right]\right\}. \tag{7}$$

A similar approach may be used to find an estimate for $\phi_{2,err}$, and results in

$$\hat{\phi}_{2,err} = \arg\left\{\hat{y}_{2,l}^*\left[y_l - \hat{y}_{1,l} e^{j\phi_{1,err}}\right]\right\}. \tag{8}$$

Figure 10 is a block diagram of embodiments of local AFC **1010** combined with embodiments of long-term AFC **1020** for a two-user case, where user one is the desired user and user two is the interferer. The output of the local AFC **1010** may be used in the equalizer, but is also output to the long-term AFC **1020**. The local AFC

output can optionally be sampled at a lower rate, which is then input to the long term AFC block.

More specifically, as shown in Figure 10, embodiments of local AFC **1010** include a phase error computation block **1030** that is configured to compute a first phase error in the first received signal and a second phase error in the second received signal based, for example, on the outputs of an MLSE. One or more second order phase locked loops **1040a** and **1040b** also may be provided. The first phase locked loop **1040a** is responsive to the first phase error, to compute a first frequency error. The second phase locked loop **1040b** is responsive to the second phase error, to compute a second frequency error therefrom. These frequency errors then are provided to the long term AFC block **1020**, wherein smoothing blocks **1050a**, **1050b** operate as was already described.

Figure 11 is a block diagram of phase error computation, for example block **1030** of Figure 10, according to embodiments of the present invention. The phase error computation of Figure 11 generates the phase errors that are described above by Equations (7) and (8). As can be seen, each phase error estimate is used to update the other phase error estimate using a feedback process, as shown in Figure 10. Other embodiments for performing or replacing this feedback will be described below.

Figure 12 is a block diagram of second order phase locked loops, such as second order phase locked loops **1040a** and **1040b** of Figure 10, according to embodiments of the invention. Second order phase locked loops are well known to those having skill in the art and need not be described further herein.

Embodiments of the above-described local two-user AFC techniques, for example as shown in Figures 10-12 use the estimate for $\hat{\phi}_{1,err}$ to compute $\phi_{2,err}$. To avoid this interdependence on the estimates, the term $\phi_{2,err}$ may be dropped from the estimate, resulting in a form similar to that used in the Murata et al. publication.

Other embodiments can drop the feedback phase error terms from the second user when generating the phase error for the first user. Then, the phase error term for the first user can be fed back to generate the phase error for the second user, and so on for additional users.

After the phase error terms are computed for all users, the process may be repeated. Now, the phase error estimates are available from the first iteration (of phase error computation). For example, in other embodiments, the local AFC

described in Figures 10-12 may be iterated one or more times, using the newly computed phase error terms as the feedback phase errors in Figure 11.

Embodiments that can eliminate this dependence (and can eliminate the feedback phase error terms), jointly estimate both phase errors simultaneously. To do this, the metric from Equation (4) is negated:

$$\gamma = \frac{1}{N}\left|y_l - \hat{y}_l^T w_l^*\right|^2, \tag{9}$$

and the weight vector w_l^* that minimizes this metric is found. To perform this operation, the gradient is computed to get

$$\nabla_{w_l}\gamma = \frac{1}{N}\left[-\hat{y}_l^*\left(y_l - \hat{y}_l^T w_l^*\right)\right]. \tag{10}$$

Setting this to zero results in the set of linear equations $R_l w_l^* = p_l$ where $R_l = \hat{y}_l^* \hat{y}_l^T$ and $p_l = \hat{y}_l^* y_l$. However, for the two-user symbol-spaced case, this system generally is underdetermined. In general, the pseudo-inverse R^+ may be used to solve an overdetermined or underdetermined system of equations, and for the underdetermined case $R^+=R^H(RR^H)^{-1}$. Once w_l^* is found then $(\phi_{1,err},\phi_{2,err}) = \arg(w_l^*)$.

Other alternative embodiments can avoid creating an underdetermined system of equations. To do this, a fractionally-spaced set of receive samples may be used, where the fractional spacing is greater than or equal to the number of users to be jointly demodulated. For example, for a fractional sampling rate of two samples per symbol, y_l becomes the vector of receive samples $y_l=[y(lT_s-T_s/2)y(lT_s)]$, and $\hat{y}_l$ is now a 2x2 matrix. For the two-user case, a unique solution for the weight vector may be found. Another alternative embodiment to avoid creating an underdetermined system of equations is to consider two symbol-spaced samples at a time, thus performing the AFC update once every two symbols.

Other embodiments may calculate a joint phase error update in a less accurate manner. For example, in an IS-136 equalizer, the value used for the phase error update is the sign of the phase error. Thus, the update to the local AFC has a fixed magnitude, but varies in sign. A similar approach may be used for joint demodulation

embodiments. For example, in the two-user case, the pair of phase update values ($\phi_{1,err}$, $\phi_{2,err}$) could take one of the values belonging to the set {(μ_1, μ_1), (-μ_1, μ_1), (μ_1, -μ_1), (-μ_1, -μ_1)}. The exact value could be chosen by evaluating Equation (12) for each possible value of ($\phi_{1,err}$, $\phi_{2,err}$) and choosing that pair which minimizes γ. In another embodiment, the arg() function can be replaced by the approximation arg(a*b)=sign(real(a)imag(b)-real(b)imag(a)). To compute $\hat{\phi}_{2,err}$, let a = $\hat{y}_{1,l}$ and b = y_l - $\hat{y}_{2,l}$, and to compute $\hat{\phi}_{2,err}$, let a = $\hat{y}_{2,l}$ and b = y_l - $\hat{y}_{1,l}$.

Finally, neither per-survivor processing nor multiple-survivor MLSE may be required. Rather, one channel model and/or one AFC model may be sufficient for all hypothesized states (paths) in the demodulator. Thus, an alternate embodiment can use one AFC model to compute a single phase error estimate and a single frequency error estimate for all hypothesized states (paths) at each sample time. The same local AFC update approach described previously may be used, but the data used to perform the update may be taken from the best hypothesized state (path). To allow reliable estimates to be computed, a lag between the current receive sample and the sample used for updating the estimates may be present and information saved along the best path may be used in this case.

Referring now to Figures 13 and 14, embodiments that can perform adaptive demodulation according to the present invention now will be described. As shown in Figure 13, demodulation systems and methods **1300** include a joint demodulator **1310** as was described above, and also add a single-user demodulator **1320**, also referred to as a single-user detector. A selector **1330** selects either the joint demodulator **1310** or the single-user demodulator **1320** for the present slot. Accordingly, adaptive selection between joint demodulation and single user demodulation may be provided.

When joint demodulation is used, the long-term AFC can operate as was already described. When single-user demodulation is selected, there may not be a corresponding frequency update for the interferer, since the single-user demodulator need not demodulate the interferer. In this case, the interferer frequency preferably is maintained constant. In Figure 13, a multiplexer **1340** is employed to allow the interferer frequency f_2 to be maintained constant without being updated. In contrast, in Figure 14, demodulation systems and methods **1400** also use a single-user demodulator **1420** and joint demodulator **1410**, as described above, but output error frequencies. When the selector **1430** selects the single-user demodulation **1420**, then

the multiplexer **1440** can select a zero input when interference frequency errors are output by the single-user demodulator **1420** and by the joint demodulator **1410**.

Simulation results now will be presented for two-user joint demodulation systems and methods according to embodiments of the invention. Figure 15 shows the performance comparing cases for no AFC, independent AFC and joint AFC when no frequency error exists. These AFC modes are designated as AFC 0, AFC 1 and AFC 11, respectively. Also shown in this plot is a conventional demodulator with and without AFC as well as the performance with known true channel information. The number of taps assigned to the desired and interfering signals is denoted as Dn/Im, so that the conventional demodulator is represented as D1/I0. The joint demodulator uses one desired signal and three interferer taps, and is thus designated as D1/I3. Also designated are whether the channel is assumed known (TC) or estimation is used (EC), sync is known (TS) or estimated (ES), and whether the interferer misalignment is known (TM) or estimated (EM). The actual frequency offset for the desired signal and interferer is labeled as Df_d/If_i in Hz.

Figure 15 shows that in the case of conventional demodulation, AFC does not degrade performance significantly when there is no frequency offset in the desired signal. However, when joint demodulation is used with independent AFC, severe degradation of AFC performance occurs, although there is still an advantage ($\approx$ 1 dB at 1% BER) compared to conventional demodulation. Use of joint AFC restores performance to the original results when AFC is not used (and there are no frequency offsets).

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

WHAT IS CLAIMED IS:

1. A joint demodulation system for demodulating jointly received first and second signals, the joint demodulation system comprising:

a converter that is configured to downconvert the jointly received first and second signals; and

a joint demodulator that is responsive to the downconverted jointly received first and second signals, and that is configured to separately generate an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal;

wherein the converter is responsive to the estimated first frequency/first frequency error to downconvert the jointly received first and second signals; and

wherein the joint demodulator is responsive to a difference between the estimated second frequency/second frequency error and the estimated first frequency/first frequency error to jointly demodulate the downconverted jointly received first and second signals.

2. The system according to Claim 1 wherein the joint demodulator assumes that there is no first frequency error.

3. The system according to Claim 1 wherein the first signal is a desired signal and wherein the second signal is an interfering signal.

4. The system according to Claim 1 further comprising:

a first feedback loop that is coupled between the estimated first frequency/first frequency error and the converter, such that the converter downconverts the jointly received first and second signals based on the estimated first frequency/first frequency error; and

a second feedback loop that is coupled between the estimated second frequency/frequency error and the joint demodulator, such that the joint demodulator separately generates the estimated first and second frequency errors based on the estimated second frequency/second frequency error.

5. The system according to Claim 4 wherein the joint demodulator includes a first local automatic frequency control system that corrects for frequency offsets in the first signal at a first rate, and wherein the first feedback loop comprises:

a first long term automatic frequency control system that is coupled to the first local automatic frequency control system to correct for frequency offsets in the first signal at a second rate that is lower than the first rate, the first long term automatic frequency control system being coupled to the converter.

6. The system according to Claim 4 wherein the joint demodulator includes a second local automatic frequency control system that corrects for frequency offsets in the second signal at a first rate, and wherein the second feedback loop comprises:

a second long term automatic frequency control system that is coupled to the second local automatic frequency control system to correct for frequency offsets in the second signal at a second rate that is lower than the first rate, the second long term automatic frequency control system being coupled to the joint demodulator.

7. The system according to Claim 5 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

8. The system according to Claim 6 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

9. The system according to Claim 5 wherein the first local automatic frequency control comprises:

a phase error computer that is configured to compute a phase error in the first received signal at the first rate; and

a phase lock loop that is responsive to the phase error and is configured to compute a first frequency error therefrom at the first rate.

10. The system according to Claim 6 wherein the second local automatic frequency control comprises:

a phase error computer that is configured to compute a phase error in the second received signal at the first rate; and

a phase lock loop that is responsive to the phase error and is configured to compute a first frequency error therefrom at the first rate.

11. The system according to Claim 9 wherein the first long term automatic frequency control comprises:

a feedback loop that is responsive to the first frequency error and is configured to determine a second frequency error therefrom at the second rate.

12. The system according to Claim 10 wherein the second long term automatic frequency control comprises:

a feedback loop that is responsive to the first frequency error and is configured to determine a second frequency error therefrom at the second rate.

13. The system according to Claim 1 further comprising:

a single-user demodulator that is responsive to the downconverted jointly received first and second signals, and that is configured to estimate the first frequency error; and

a selector that selects the joint demodulator or the single-user demodulator.

14. The system according to Claim 13 wherein the estimated second frequency error is maintained constant when the selector selects the single-user demodulator.

15. A joint demodulation system for demodulating jointly received first and second signals, the joint demodulation system comprising:

a converter that is configured to downconvert the jointly received first and second signals;

a joint demodulator that is responsive to the downconverted jointly received first and second signals, and that is configured to separately generate an estimate of a first frequency/first frequency error for the downconverted first signal and an estimate

of a second frequency/second frequency error in the downconverted second signal; and

wherein the joint demodulator is responsive to both the estimated second frequency/second frequency error and the estimated first frequency/first frequency error to jointly demodulate the downconverted jointly received first and second signals.

16. A joint demodulation system according to Claim 15 further comprising:

a first feedback loop that is coupled between the estimate of a first frequency/first frequency error and the joint demodulator, such that the joint demodulator demodulates the jointly received first and second signals based on the estimate of a first frequency/first frequency error; and

a second feedback loop that is coupled between the estimate of the second frequency error and the joint demodulator, such that the joint demodulator also demodulates the jointly received first and second signals based on the estimate of the second frequency/second frequency error.

17. The system according to Claim 15 wherein the first signal is a desired signal and wherein the second signal is an interfering signal.

18. The system according to Claim 15 wherein the joint demodulator includes a first local automatic frequency control system that corrects for frequency offsets in the first signal at a first rate, and wherein the first feedback loop comprises:

a first long term automatic frequency control system that is coupled to the first local automatic frequency control system to correct for frequency offsets in the first signal at a second rate that is lower than the first rate, the first long term automatic frequency control system being coupled to the joint demodulator.

19. The system according to Claim 15 wherein the joint demodulator includes a second local automatic frequency control system that corrects for frequency offsets in the second signal at a first rate, and wherein the second feedback loop comprises:

a second long term automatic frequency control system that is coupled to the second local automatic frequency control system to correct for frequency offsets in the second signal at a second rate that is lower than the first rate, the second long term automatic frequency control system being coupled to the joint demodulator.

20. The system according to Claim 18 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

21. The system according to Claim 19 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

22. The system according to Claim 18 wherein the first local automatic frequency control comprises:

a phase error computer that is configured to compute a phase error in the first received signal at the first rate; and

a phase lock loop that is responsive to the phase error and is configured to compute a first frequency error therefrom at the first rate.

23. The system according to Claim 19 wherein the second local automatic frequency control comprises:

a phase error computer that is configured to compute a phase error in the second received signal at the first rate; and

a phase lock loop that is responsive to the phase error to compute a first frequency error therefrom at the first rate.

24. The system according to Claim 22 wherein the first long term automatic frequency control comprises:

a feedback loop that is responsive to the first frequency error and is configured to determine a second frequency error therefrom at the second rate.

25. The system according to Claim 23 wherein the second long term automatic frequency control comprises:

a feedback loop that is responsive to the first frequency error to determine a second frequency error therefrom at the second rate.

26. The system according to Claim 15 further comprising:

a single-user demodulator that is responsive to the downconverted jointly received first and second signals, and that is configured to provide the estimate of the first frequency/first frequency error; and

a selector that selects the joint demodulator or the single-user demodulator.

27. The system according to Claim 26 wherein the second feedback loop maintains the estimate of the second frequency error constant when the selector selects the single-user demodulator.

28. A demodulation system for jointly received first and second signals, comprising:

a joint demodulator that is configured to generate an estimated first frequency/first frequency error for the first signal and an estimated second frequency/second frequency error for the second signal;

a first long term automatic frequency control that is responsive to the estimated first frequency/first frequency error, wherein the joint demodulator is responsive to the first long term automatic frequency control; and

a second long term automatic frequency control that is responsive to the estimated second frequency/second frequency error, wherein the joint demodulator is responsive to the second long term automatic frequency control.

29. The system according to Claim 28 further comprising:

a subtractor that is responsive to the first and second and second automatic frequency controls, wherein the joint demodulator is responsive to the subtractor.

30. The system according to Claim 28 further comprising:

a converter that is configured to downconvert the jointly received first and second signals;

wherein the joint demodulator that is responsive to the downconverted jointly received first and second signals; and

wherein the converter also is responsive to the first long term automatic frequency control.

31. The system according to Claim 28 wherein the first signal is a desired signal and wherein the second signal is an interfering signal.

32. The system according to Claim 28 wherein the joint demodulator includes a first local automatic frequency control that corrects for frequency offsets in the first signal at a first rate, and wherein the first long term automatic frequency control is coupled to the first local automatic frequency control to correct for frequency offsets in the first signal at a second rate that is lower than the first rate.

33. The system according to Claim 28 wherein the joint demodulator includes a second local automatic frequency control that corrects for frequency offsets in the second signal at a first rate, and wherein the second long term automatic frequency control is coupled to the first local automatic frequency control to correct for frequency offsets in the first signal at a second rate that is lower than the first rate.

34. The system according to Claim 32 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

35. A joint demodulation method for demodulating jointly received first and second signals, the joint demodulation method comprising:

downconverting the jointly received first and second signals; and

separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal;

wherein the downconverting the jointly received first and second signals is responsive to the estimated first frequency/first frequency error; and

wherein the separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal is responsive to a difference between the estimated second frequency/second frequency error and the estimated first frequency/first frequency error.

36. The method according to Claim 35 wherein the first signal is a desired signal and wherein the second signal is an interfering signal.

37. The method according to Claim 35 wherein the separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal comprises:

correcting for frequency offsets in the first signal at a first rate; and

correcting for frequency offsets in the frequency offset corrected first signal at a second rate that is lower than the first rate, to thereby estimate the first frequency/first frequency error.

38. The method according to Claim 35 wherein the separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal comprises:

correcting for frequency offsets in the second signal at a first rate; and

correcting for frequency offsets in the frequency offset corrected second signal at a second rate that is lower than the first rate, to thereby estimate the second frequency/second frequency error.

39. The method according to Claim 38 wherein the jointly received first and second signals are received over a series of repeating slots and are sampled more than once during each slot, wherein the first rate is once per sample and wherein the second rate is once per slot.

40. The method according to Claim 37 wherein the correcting for frequency offsets in the first signal at a first rate comprises:

computing a phase error in the first received signal at the first rate; and

computing a first frequency error therefrom at the first rate.

41. The method according to Claim 35 further comprising:

estimating the first frequency error in the downconverted first signal; and

selectively performing the separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal or the estimating the first frequency error in the downconverted first signal.

42. The method according to Claim 41 further comprising maintaining the estimated second frequency/second frequency error constant in response to the selectively performing the estimating the first frequency error in the downconverted first signal.

43. A joint demodulation method for demodulating jointly received first and second signals, the joint demodulation method comprising:

downconverting the jointly received first and second signals;

separately generating an estimate of a first frequency/first frequency error for the downconverted first signal and an estimate of a second frequency/second frequency error in the downconverted second signal;

wherein the separately generating an estimated first frequency/first frequency error for the downconverted first signal and an estimated second frequency/second frequency error for the downconverted second signal is responsive to both the estimated second frequency/second frequency error and the estimated first frequency/first frequency error.

44. The method according to Claim 43 wherein the first signal is a desired signal and wherein the second signal is an interfering signal.

AUTOMATIC FREQUENCY CONTROL SYSTEMS AND METHODS FOR JOINT DEMODULATION

ABSTRACT OF THE DISCLOSURE

A joint demodulator is configured to generate an estimated first frequency or first frequency error for the first signal and an estimated second frequency or second frequency error for the second signal. A first long-term automatic frequency control is responsive to the estimated first frequency or first frequency error, wherein the joint demodulator is responsive to the first long-term automatic frequency control. A second long-term automatic frequency control is responsive to the estimated second frequency or second frequency error, wherein the joint demodulator is responsive to the second long-term automatic frequency control. First and second local automatic frequency controls also may be included in the joint demodulator, wherein the first long-term automatic frequency control is responsive to the first local automatic frequency control and the second long-term automatic frequency control is responsive to the second local automatic frequency control. The first long-term automatic frequency control and the second long-term automatic frequency control can produce respective first and second frequency offset signals that are applied to the joint demodulator. Alternatively, a difference between the first and second frequency offsets is applied to the joint demodulator and the first frequency offset is applied to a downconverter that downconverts the jointly received first and second signals and provides the downconverted signals to the joint demodulator.

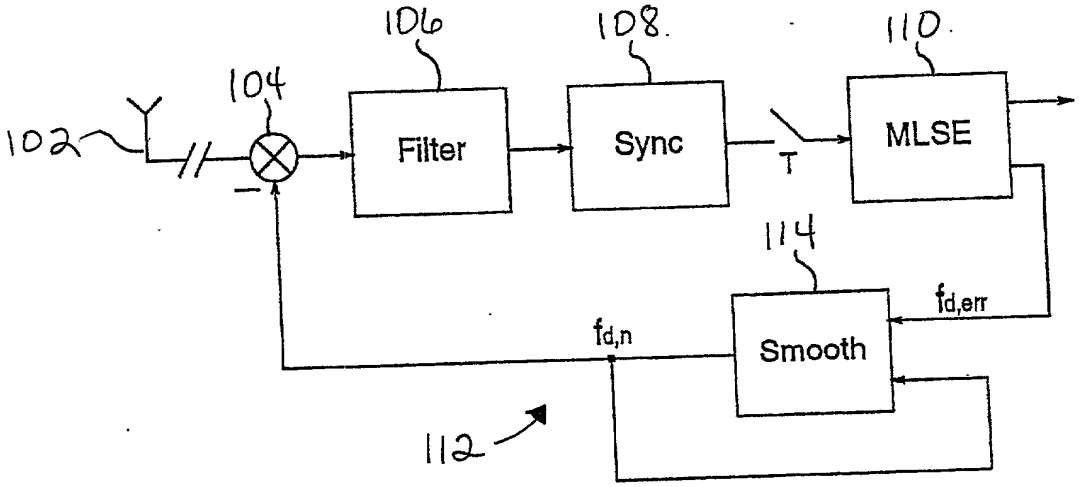


FIGURE 1
(PRIOR ART)

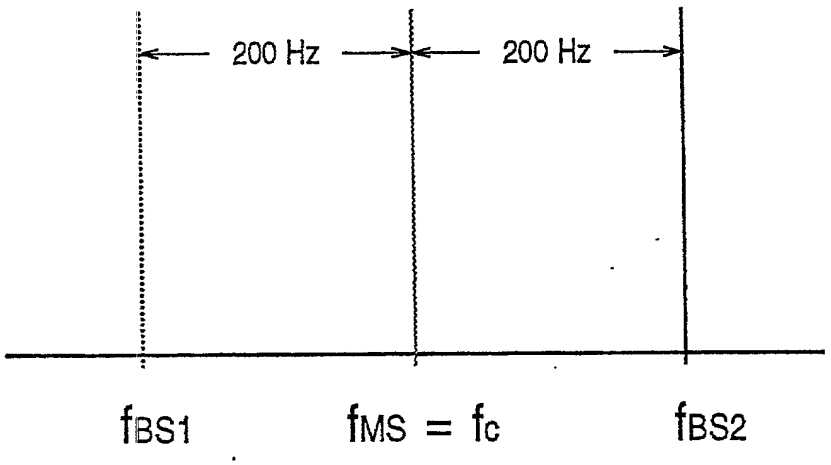


FIGURE 2

FIGURE 3

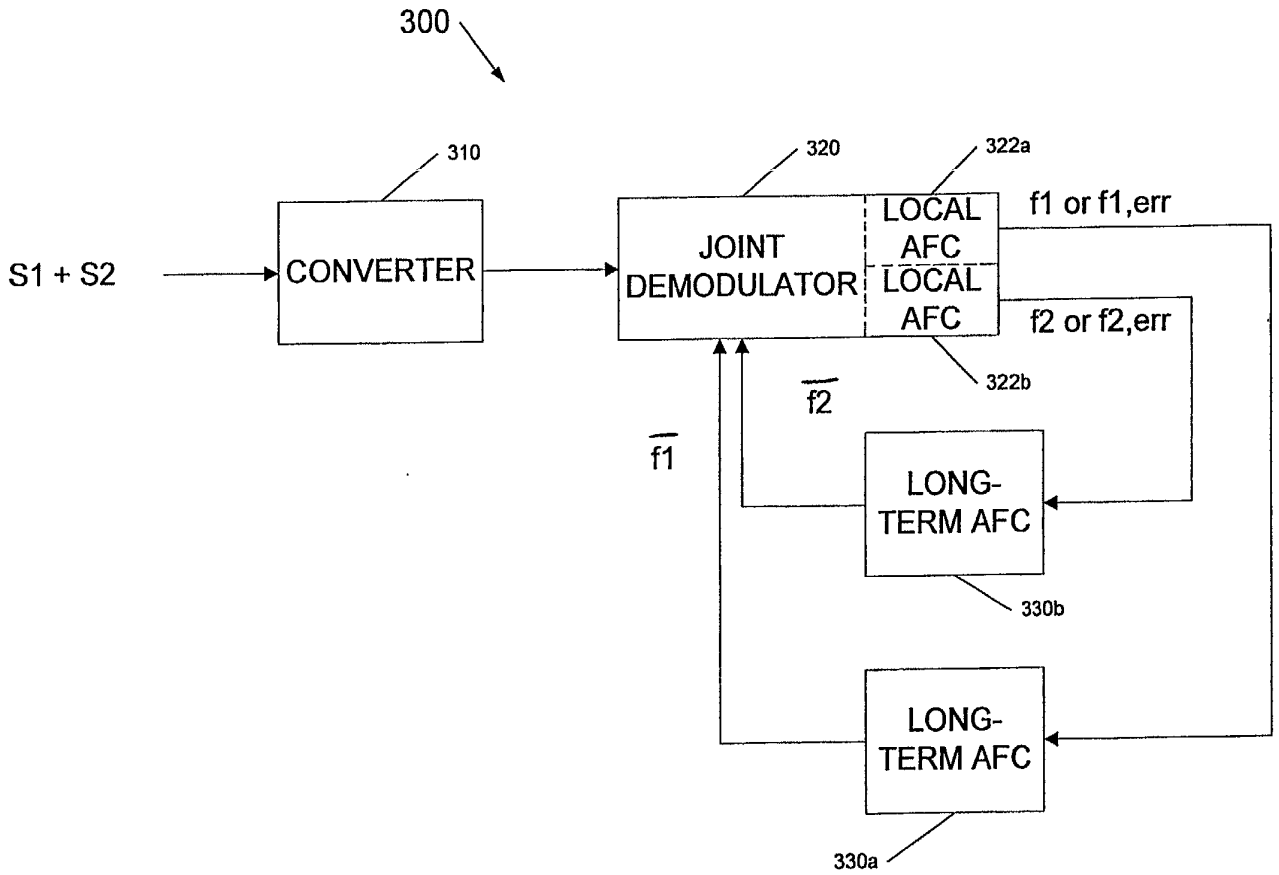
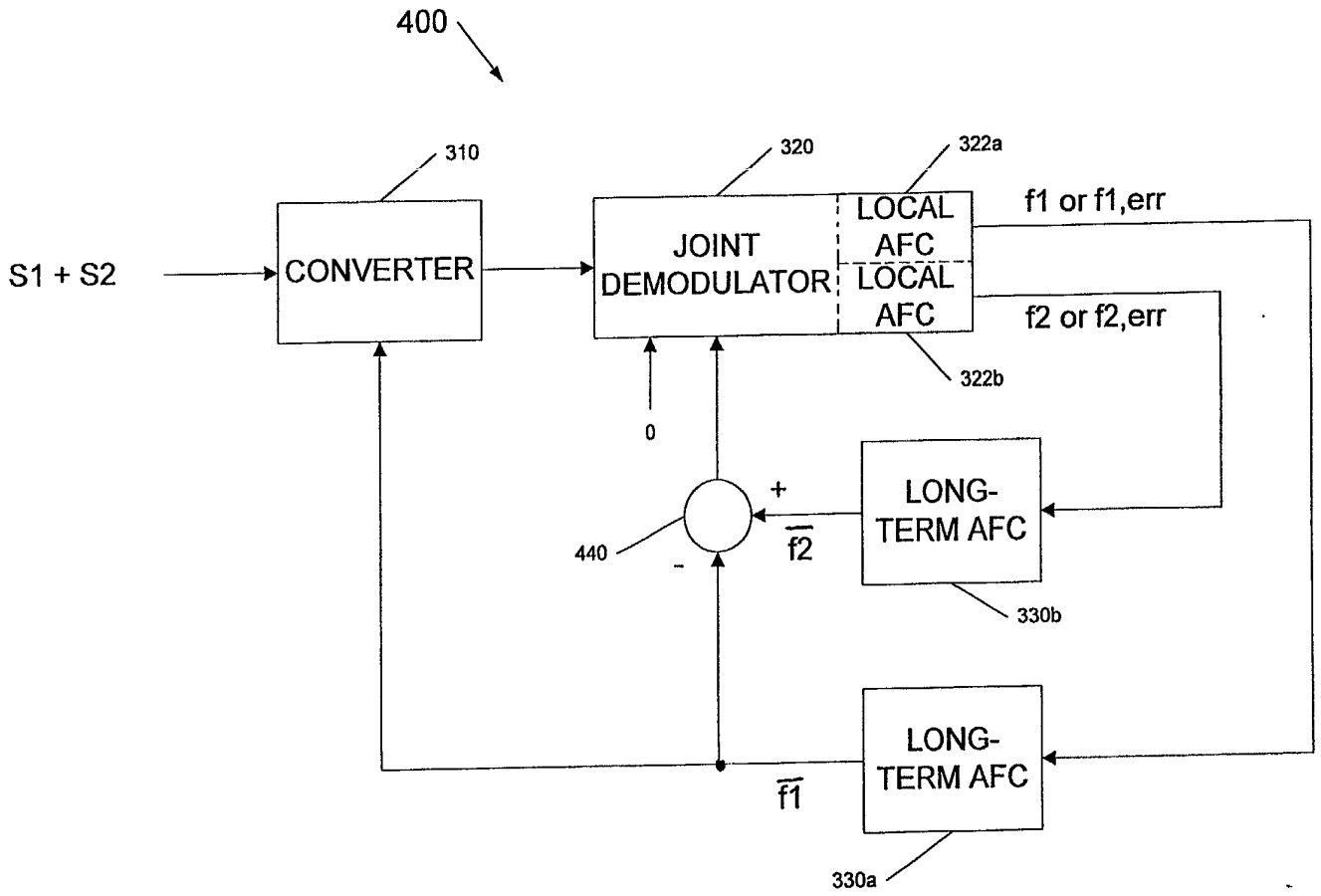

300
310
320
322a
S1 + S2
CONVERTER
JOINT DEMODULATOR
LOCAL AFC
LOCAL AFC
f1 or f1,err
f2 or f2,err
322b
f2
f1
LONG-TERM AFC
330b
LONG-TERM AFC
330a

FIGURE 4


400
310
320
322a
S1 + S2
CONVERTER
JOINT DEMODULATOR
LOCAL AFC
LOCAL AFC
f1 or f1,err
f2 or f2,err
322b
0
+
440
-
$\overline{f2}$
LONG-TERM AFC
330b
LONG-TERM AFC
$\overline{f1}$
330a

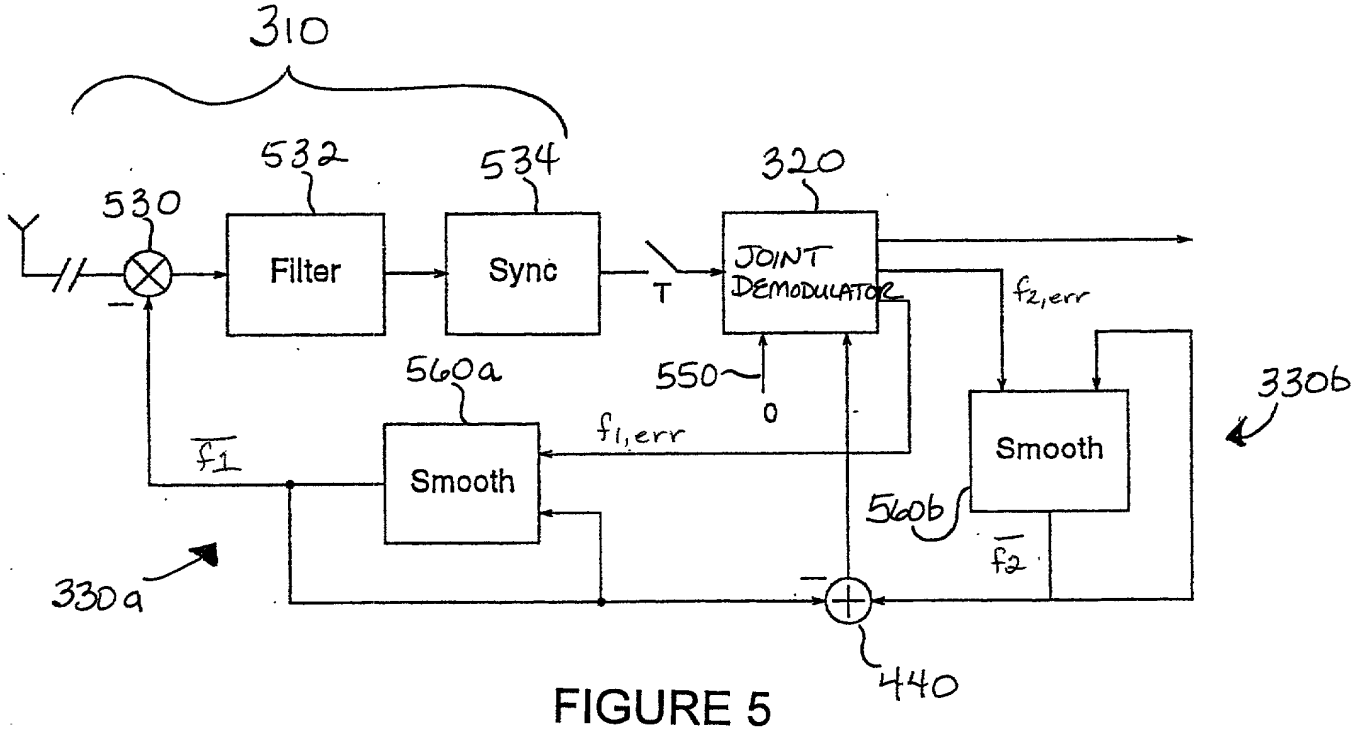


FIGURE 5

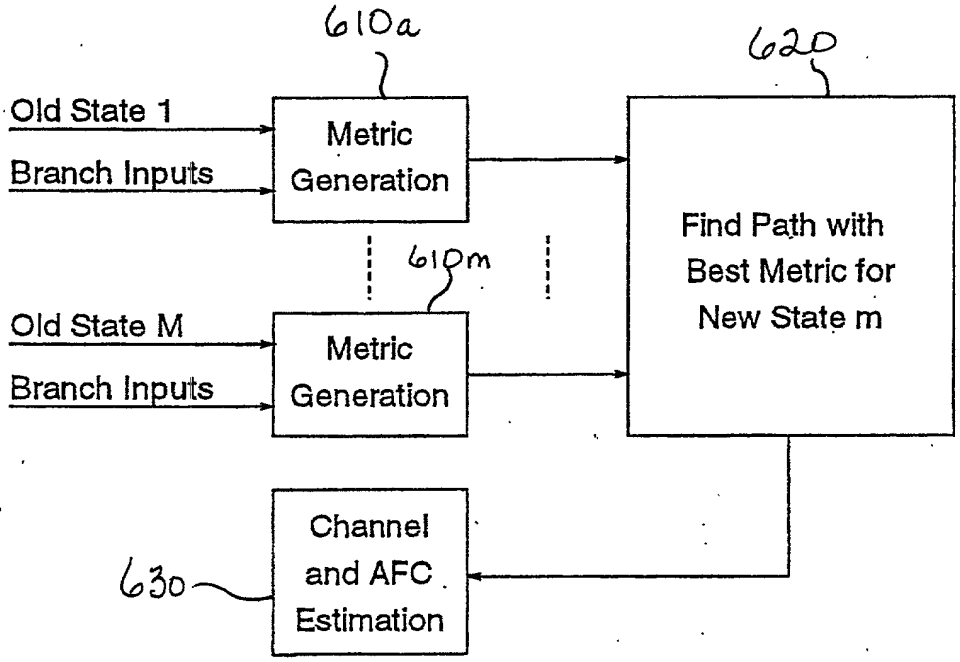


FIGURE 6

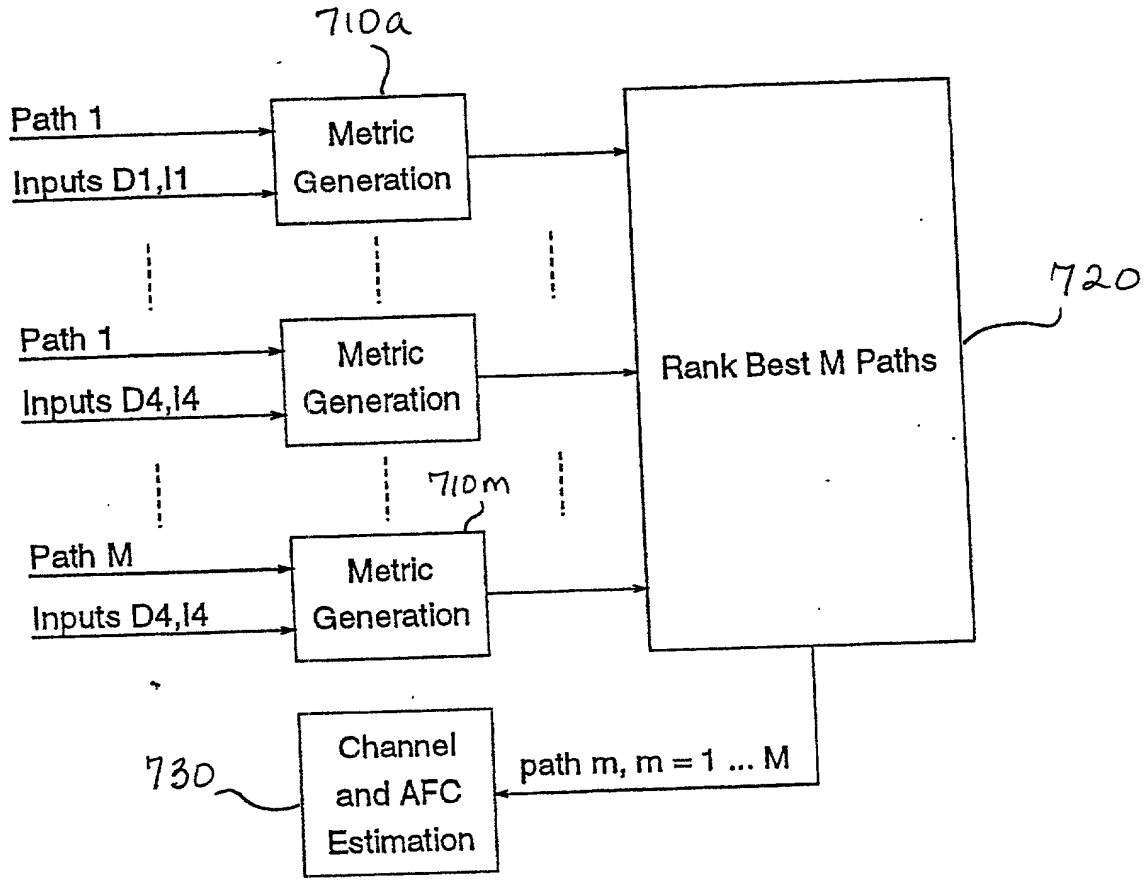


FIGURE 7

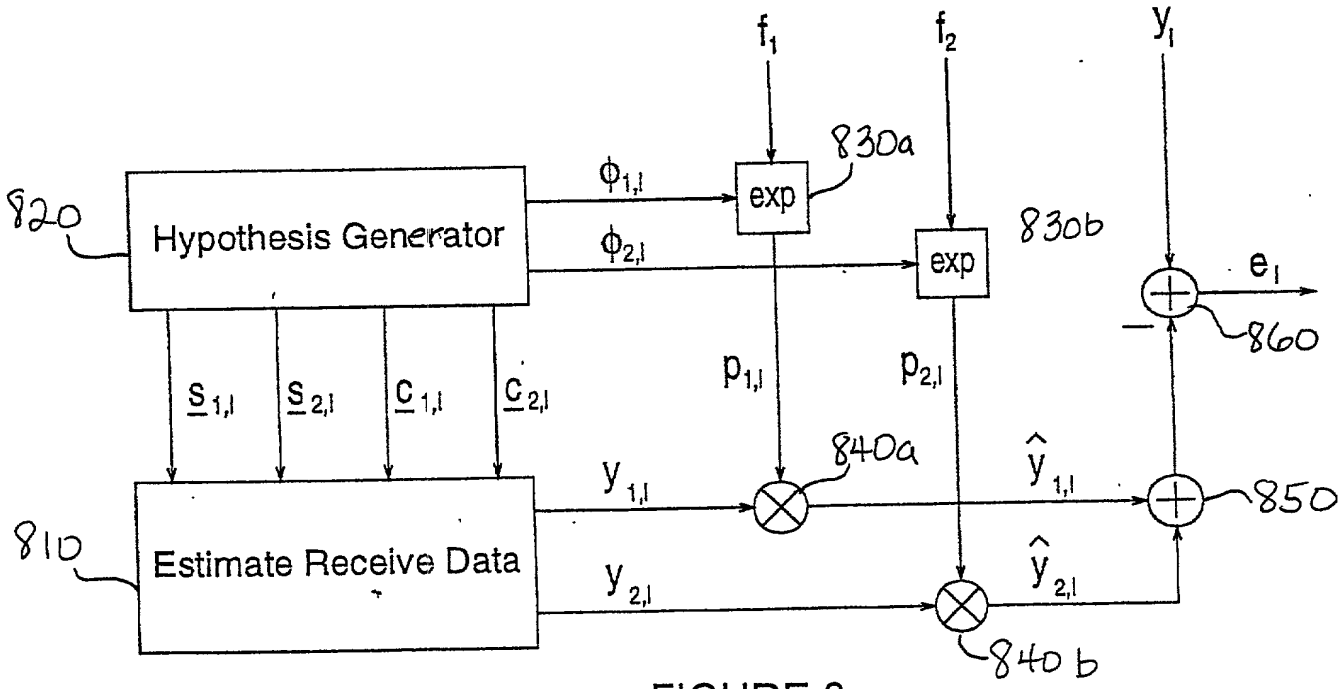


FIGURE 8

FIGURE 10

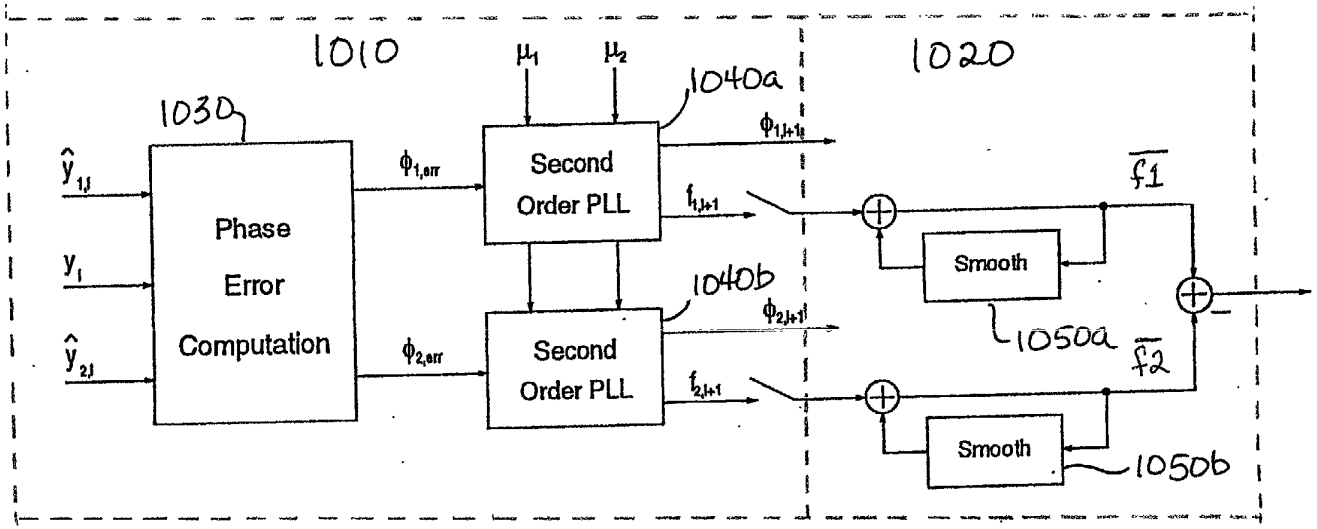
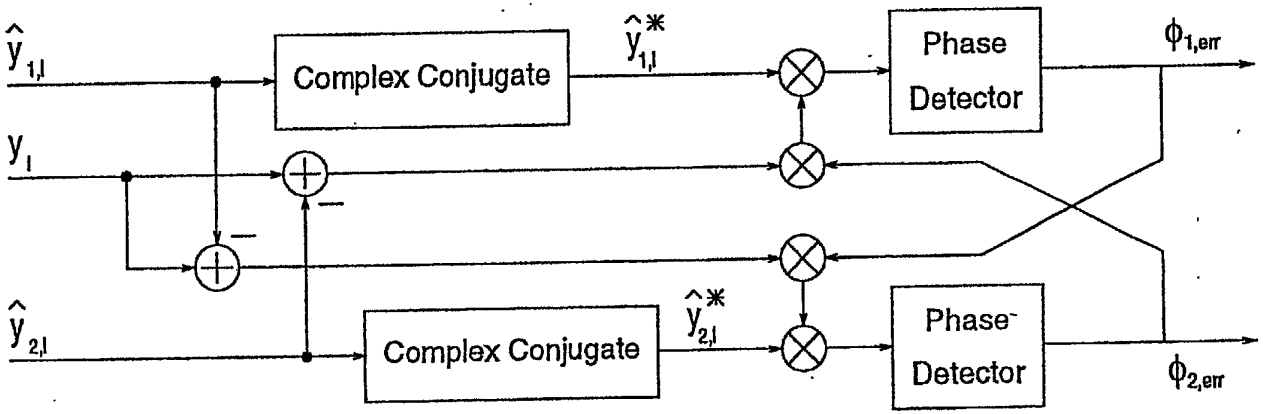


FIGURE 11



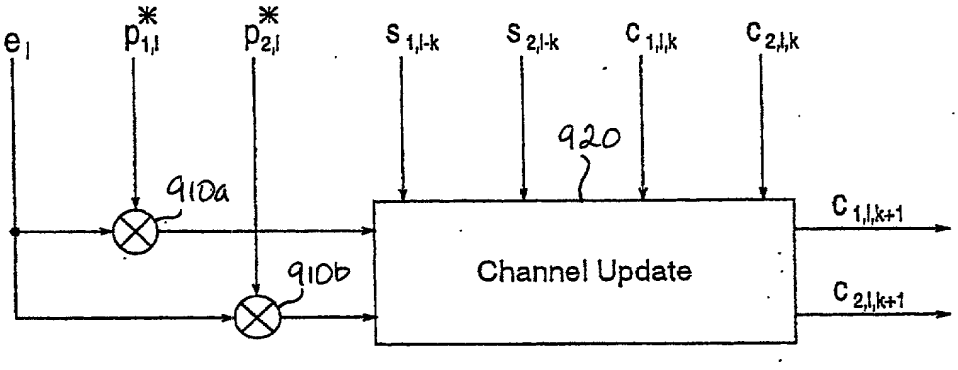


FIGURE 9

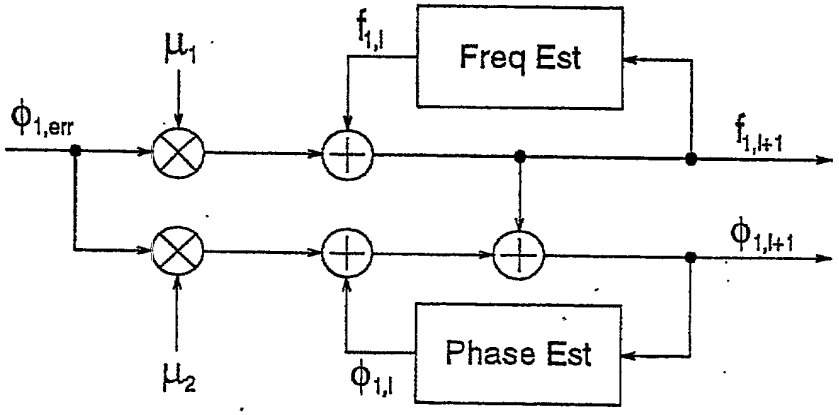


FIGURE 12

FIGURE 13

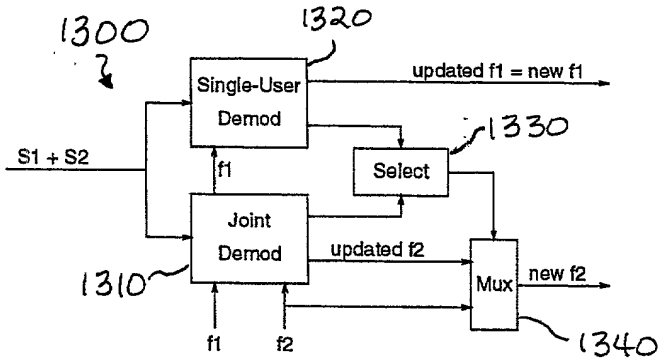
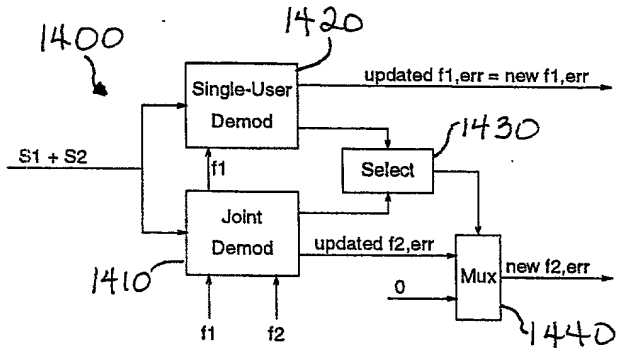


FIGURE 14



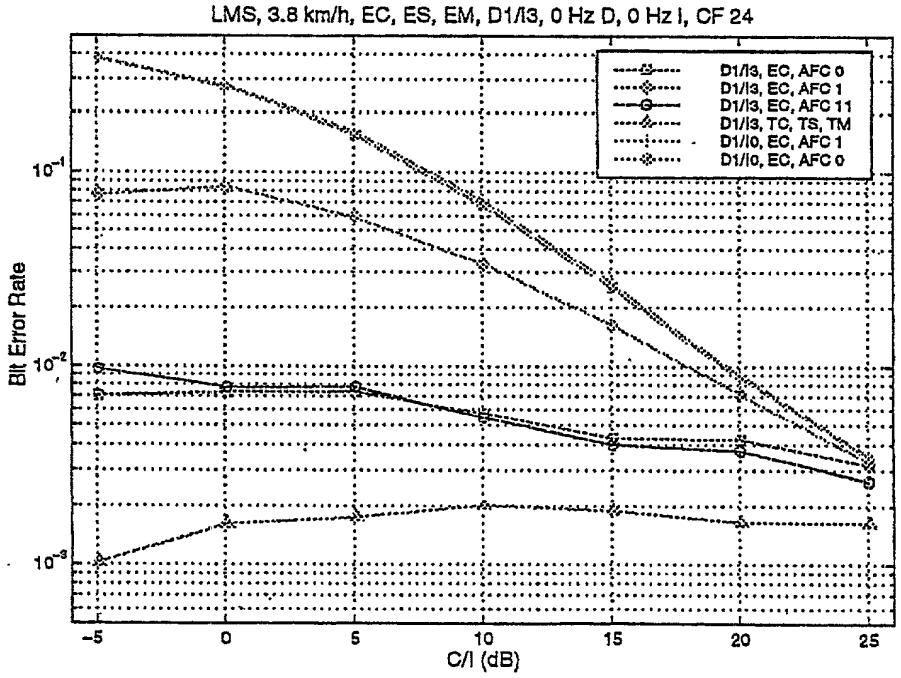


FIGURE 15